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EXPERIMENTS IN THE USE OF FERTILIZERS IN GROWING FOREST PLANTING MATERIAL AT THE SAVENAC NURSERY

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INTRODUCTION

The history of forest-nursery practice in older countries indicates that in the long run soil fertility can not be adequately maintained by the simple use of a moderate crop rotation and leguminous cover crops. As pointed out by Toumey (*31*),[1] extensive experiments conducted in Europe by Heck, Grunder, Kienitz, Engler, Schwappach, Möller, Reuss, and others prove the necessity for the liberal use of fertilizers in permanent forest nurseries. Experience in many places has shown beyond any reasonable doubt that the bulky fertilizers of organic origin are the best, but unfortunately they are also the most expensive if, as often happens, they have to be shipped from a distance. Unless abundant compost or animal manure is locally available, some of the more highly concentrated commercial fertilizers must be used to make up the deficiency. Just which ones are best to use can only be determined by local experiments with crops and soil.

Reviewed in chronological order, the experiments at Savenac Nursery, Haugan, Mont., naturally fall into three separate groups, each emphasizing a fairly distinct aim: (1) Improvement of the planting stock; (2) stimulation of the rate of seedling growth; and (3) maintenance of soil productivity. The first group of tests filled a less imperative need and was less intensively handled than those that followed. The second group of tests was pursued in-

[1] Italic numbers in parentheses refer to Literature Cited, p. 35.

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tensively for six years and supplied an answer to one specific problem dealing with one species of tree. The third group of tests has also been intensively handled, but because of the broad scope of its aims it is still incomplete. The final solution will require observation through many years; the two years already devoted to it supply at best only preliminary results.

EARLY EFFORTS TO IMPROVE PLANTING STOCK [2]

Early experimentation with fertilizers at Savenac was attempted with the sole idea of improving forest-planting stock. During three years dried blood, sheep manure, nitrate of soda, sulphate of potash, superphosphate, and bone meal were tried out more or less extensively. The materials were either spaded in or applied in solution. A combination of dried blood and bone meal was recognized as giving the best results, and this agreed with contemporary nursery practice in which 2 pounds of dried blood and 1 pound of ground bone were applied to each 48 square feet. Pine seedlings responded most favorably to this early treatment but showed some signs of increased susceptibility to disease. This was attributed to the heavy nitrogenous fertilization, but may have been due to unbalanced nutrition or what Moir (*21*) calls lack of a proper food balance. Although the fertilized trees grew slightly faster in the field plantations, fewer of them survived as compared with the unfertilized trees. Anything decreasing the hardiness of planting stock is to be avoided, and these results were therefore discouraging, even though there is reason to believe that the lower survival of fertilized trees was due to some extraneous cause. The short root pruning previous to planting in vogue in those early days may easily have increased top-heaviness of the fertilized trees much more than it did that of the unfertilized trees. However this may have been, no further experimental work with fertilizers was done until six years later.

STIMULATION OF ENGELMANN SPRUCE GROWTH

The purpose of the group of experiments extending from 1921 to 1926 was to determine an effective and safe method of so stimulating the growth of Engelmann spruce (*Picea engelmannii*) in nursery seed beds as to reduce the time required to produce plants large enough to handle in field planting operations. Under the methods of culture in vogue when this work was started, spruce seedlings were too small to be handled until 5 years old and transplants were too small until 6 years old. If these required periods could be shortened by one or more years, the economy in the use of nursery space and money would be considerable. It was recognized that plant growth may be stimulated in many ways under artificial conditions involving the control of temperature, humidity, light, concentration of carbon dioxide in the atmosphere, etc., but because methods of this kind would probably involve prohibitive costs attention was turned to the use of water and fertilizer as a more practical solution.

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[2] These experiments were made by Elers Koch, E. C. Rogers, T. P. Maloy, and P. C. Kitchin.

USE OF HEAVY WATERING AND A MIXTURE OF DRIED BLOOD AND GROUND BONE AS FERTILIZERS

The effect which a high soil moisture content may have on the development of spruce seedlings was accidentally illustrated in the nursery, where an irrigation ditch passed close by the corner of a seed bed. Running water behind the embankment of the ditch passed within 1 foot of the nearest seedlings. Where the soil was maintained in an unusually moist condition as a result of subirrigation from the ditch the seedlings were especially large. Plans for the experiments which were started in 1921 were based upon this clue and upon a few encouraging previous trials of blood and bone as fertilizers. Dried blood is especially rich in readily soluble nitrogen, an element in which the nursery soil seems to be deficient. Ground bone contains some nitrogen but is especially rich in phosphorus; it is recommended for slow-growing crops because its nutrients become available gradually.

INSTALLATION AND CARE OF BEDS IN 1921

During the last week of April, 1921, four 4 by 12 foot beds were established, two to receive ordinary care and the other two to be heavily watered. Each bed was divided into four plots of 12 square feet each. Each plot was surrounded by a board frame extending 8 inches below the surface. The frames were designed for the purpose of providing soil partitions adequate to prevent the capillary movement of the soil solution from one plot to another. They permitted a desirable alternation of test and check plots within the same bed. Lath and screens provided the necessary half shade and protection from birds and animals.

The fertilizers were mixed in the ratio of 1 part by weight of dried blood to 2 parts of bone meal. Duplicate plots in one bed were fertilized at the rate of 3 pounds of this mixture per 48 square feet, and similar duplicate plots in another bed were fertilized at one-half this rate. These beds were watered as in ordinary nursery practice. The other two beds, which were to be heavily watered, were prepared and fertilized in the same way, one with a light and the other with a heavy application of fertilizer. Each bed also contained two unfertilized check plots alternating with the test plots.

The soil, which had been thoroughly loosened in inserting the wooden frames and in mixing the fertilizers into the upper 4 or 5 inches, was tamped slightly to avoid subsequent uneven settling of the surface following sprinkling. The slight irregularities in the surface created by the tamping were filled with sifted unfertilized soil and accurately leveled. This unfertilized layer of soil was about one-eighth of an inch in thickness. On it in each plot 2,000 spruce seeds were sown and covered with one-eighth of an inch of sifted sand.

All artificial sprinkling was done with a can graduated to show fluid units in terms of rainfall equivalents per bed of 48 square feet. During the dry summer seasons the normally watered beds were given the equivalent of 0.08 inch of rainfall nearly every day and the other beds 0.16 inch. The purpose was to keep the heavily watered beds as moist as possible without loss of any water from surface run-off. At the end of each growing season the amount of water applied to each bed was added to the rainfall for the same

period as measured in a standard gauge. The quantities of water received by the beds from May to October were much the same for each of the first three years, the totals for the three years being 32.96 inches for the normal beds, and 55.83 inches, or an increase of 69 per cent, for the heavily watered beds.

GERMINATION, LOSS, AND CAUSES OF LOSS

At the end of the first year it was apparent that directly or indirectly the fertilizers seriously reduced the numbers of seedlings emerging from the soil. This was particularly true of the heavy applications of fertilizer and on the normally watered plots. The fertilizers seemed to have reduced germination directly by adding enough readily soluble material to the soil to produce injurious concentration in the soil solution. Heavy watering appeared to check this loss indirectly by its action in diluting the soil solution and causing some of the injurious substances to leach out. This seems to agree with a conclusion reached by Sievers and Holtz (*29*). Their warning is that the influence of soil moisture on crop yield should be interpreted rather on the basis of its effect on the processes that provide available plant food than on the plant itself, if inconsistencies in interpretation of data are to be avoided. Heavy watering of the unfertilized plots at the Savenac Nursery had little effect on germination of seed.

At the end of the first growing season the trees in all plots were uniformly small; in fact, too tiny to permit of ready comparisons in size. These 1-year-old seedlings probably drew nourishment from their cotyledons for some time and apparently could obtain the small additional nourishment they required from unfertilized soil as easily as from the richer soil.

Although the causes of heavy losses in germination escaped detection, the most plausible theory was that damping-off fungi had killed many seeds after they sprouted but before they emerged above the surface. At the Wind River nursery it was observed that heavy nitrogenous fertilization made the soil a better medium for fungi, and that neutral, slightly acid, or slightly basic soils only favored damping-off. All of these conditions existed in the plots that suffered most. According to Hartley (*14*) subsurface damping-off ranks high among the usual types of loss in germination and may be caused by any of the organisms commonly capable of producing the better known manifestations of damping-off disease.

In the belief that the fertilizers themselves may have been the source of fungous infection, special tests of this possibility were made in the laboratory. Samples of spruce seeds were soaked in a solution of the fertilizers in distilled water, and other samples were stored in each of the dry fertilizers. The seeds were tested in an improvised Jacobsen germinator, which has been described by Larsen (*20*), but no differences that could be attributed to damping-off were found either in the numbers germinating or the condition of seeds. It is probable that infection by actual contact of hyphae with the radicle occurred less easily in the germinator than in the seed beds. The large mass of mycelium in the soil may also have been a significant factor. Another theory concerning the seed-bed trouble was

that the fertilizers may have changed the specific heat of the soil in such a way as to cause injurious temperatures. But actual measurements in the plots of surface temperatures in direct sunlight gave no evidence in favor of such a theory.

ADDITIONAL GERMINATION TESTS

In the spring of 1922, 12 more plots were established for the purpose of testing other combinations of fertilizer and with the hope of detecting the cause of germination loss. Sterilized loam was used in two of four unfertilized control plots, as well as in the test plots, in the hope of discouraging fungous activity. In the sterilization process soil was removed from the plot frames to a depth of 4 inches and, by subjecting it to steam, was heated to a temperature of about 70° C. for about two hours. In order to confine the soil solution and to eliminate border influences each plot was provided with wooden soil walls 8 inches deep as in the previous tests. Heavy applications of sheep manure, as suggested by the results of early work, were tested in duplicate plots. Three pairs of plots were fertilized with blood and bone in various ways, each pair testing a heavy and a light application. In two plots the materials were used in the original ratio of 1 to 2; in another pair the ratio was reversed. In the third pair, wood ashes were introduced in order to add potash to the materials carrying phosphorus and nitrogen. The quantities applied are shown in Table 1.

TABLE 1.—*Effect of certain fertilizer treatments on germination and loss of Engelmann spruce*

Fertilization ingredients	Quantity [1]	Germination [2]	Loss [2]		Survival [2]
			From fungus	Total	
	Pounds	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Sheep manure	30	26.5	1.0	1.0	25.5
Do	15	23.5	1.0	1.5	22.0
Dried blood	1	25.5	2.0	3.5	22.0
Ground bone	2				
Dried blood	½	22.5	1.0	4.5	18.0
Ground bone	1				
Dried blood	2	29.0	5.0	9.0	20.0
Ground bone	1				
Dried blood	1	25.5	4.0	6.5	19.0
Ground bone	½				
Dried blood	1	15.0	2.5	8.5	6.5
Ground bone	3				
Wood ashes	16				
Dried blood	½	25.0	4.0	7.5	17.5
Ground bone	1½				
Wood ashes	8				
Sterile check	0	25.0	0	0	25.0
Nonsterile check	0	23.0	0	0.5	22.5

[1] Per bed of 48 square feet. [2] Percentages are based on the numbers of seeds sown.

From German researches extending over 11 years with objects similar to those of this study, Helbig (*15*) reported that full fertilization with potash, basic slag, and nitrates applied to 2-year-old spruce transplants resulted in greater height growth than did partial fertilization with nitrates only. The conclusion was that fertilization of young spruce with nitrates alone is not profitable, but

that fertilization with nitrates and other materials containing phosphorus and potassium is advantageous in cases where tall planting stock is desired at an early age.

At the Savenac Nursery an equal number of seeds was sown in each plot, and during the season the plots were sprinkled normally by hand. Germinations were counted and losses recorded at 10-day intervals. Results are summarized in Table 1.

Information on stimulation of growth was not available from the work of the first year. Table 1 reveals some points regarding germination and loss. It is probable that loss from fungi was actually somewhat greater than is indicated in the table, because such loss frequently can not be distinguished definitely. Deaths were attributed to fungi only in obvious cases.

The total number of seeds sprouting was distinctly lower in the plot heavily fertilized with blood, bone, and ashes, perhaps because of the burning action of lye in the ashes. None of the other plots showed any clearly significant differences in germination. The plots receiving dried blood, ground bone, and wood ashes, and those receiving blood and bone in the 2 to 1 ratio, suffered the greatest loss. This seems to have been due in part at least to fungous attacks. Because fungi appeared to be entirely inactive in both the sterilized and unsterilized check plots, nothing could be learned regarding the effectiveness of the soil sterilization. On the other hand the presence of damping-off fungi in all fertilized plots and their absence from all check plots indicated that the fertilizers improved the soil as a medium for these organisms. That this action did not cause alarmingly large losses, as it apparently did in the previous tests, was the most encouraging result of the work.

Four additional standard 4 by 12 foot seed beds of four plots each, equipped with the same kind of soil partitions and frames (half-shade and protective screens) that were used the previous year, were sown in 1922. Eight unfertilized check plots alternated with the test plots. Two plots were fertilized at the rate of 2 pounds of dried blood and 1 pound of ground bone per 48 square feet, and another two plots were fertilized at half this rate. A pair of the plots was fertilized at the rate of 30 pounds of sheep manure per 48 square feet, and another pair was given half the amount. Although not observed as closely during their first year as those just discussed, these beds served as rough checks on the deductions already made concerning loss and survival. Plots treated with dried blood and ground bone, particularly those receiving the larger quantities, showed a greater mortality of seedlings caused by fungi. Plots fertilized with both kinds of fertilizer showed a survival nearly one-fourth higher on the lightly fertilized than on the heavy fertilized soil.

Although the failure of all these tests to show the cause of the losses in germination was discouraging from the technical viewpoint, the successful germination of seeds in the second trials was gratifying from the practical point of view, thus encouraging further studies of the development of the plant material under these various treatments.

DEVELOPMENT OF 2-0, 3-0, 4-0, AND 2-2 STOCK[3]

Differentiation in growth as a result of differences in fertilization was manifest at the end of the second season in the nursery. The beds containing plots that had been fertilized in the spring of 1921 developed seedlings to an extent that promised to outweigh the initial disadvantages in germination loss. Growth had been stimulated slightly by heavy watering, and the fertilizer—heavy and light applications of dried blood and ground bone in the 1 to 2 ratio—had caused a marked stimulation in height growth, in stem and bud development, and apparently in general thrift of the plants.

From the sowings made in the spring of 1922, similar growth was obtained from the use of blood and bone in the reversed ratio, and from sheep manure. The results are illustrated in Figures 1, 2, and 3. The pictures show that relatively the best development was attained by the trees fertilized with 30 pounds of sheep manure per bed of 48 square feet. Soil productivity in these plots may have been augmented as much by the humus content as by the nutrient content of the manure. Such use of sheep manure represents an exceedingly heavy application of a bulky fertilizer, and one which freight cost will probably prohibit.

Fortunately freight cost does not preclude the use of blood and bone, to which the trees responded nearly as well. The trees in all plots fertilized with these materials in either ratio were not only about twice as tall as the unfertilized trees but also were superior in thickness of stem, color of foliage, size of buds, and general development. In contrast the tree seedlings grown on unfertilized soil were decidedly yellowish and puny. In two years' time spruce seedlings were produced on fertilized soil that were apparently equivalent to those ordinarily produced in three years on unfertilized soil. Some of the seedlings were transplanted in the spring of 1923, but all were retained in the nursery because none of them were yet large enough for field planting.

By the end of another growing season the fertilized 3-0 seedlings were considered large enough to be planted. In lifting the seedlings from the nursery beds for use in the field certain representative lots of which typical specimens are shown in Figure 4, were segregated for anatomical examination in the laboratory. Some of the unfertilized seedlings were allowed to remain in the seed beds until 4 years old, to see if they would then have developed as well as the 3-year-old fertilized trees. The contrast in development of these seedlings is shown by the figures given in Table 2.

These figures indicate that, except on heavily fertilized plots, heavy watering resulted in larger plants with a slight tendency toward top-heaviness.

[3] In nursery practice the age of plant stock is indicated by figures, the first indicating the number of growing seasons in seed beds, the second the number in transplant rows. Thus 1-2 and 2-1 stocks are both 3 years old, but may differ in development because of the difference in time of nursery transplanting. They are called transplants, whereas 2-0 and 3-0 trees are 2 and 3 years old, respectively, and because they were not moved in the nursery, are called seedlings.

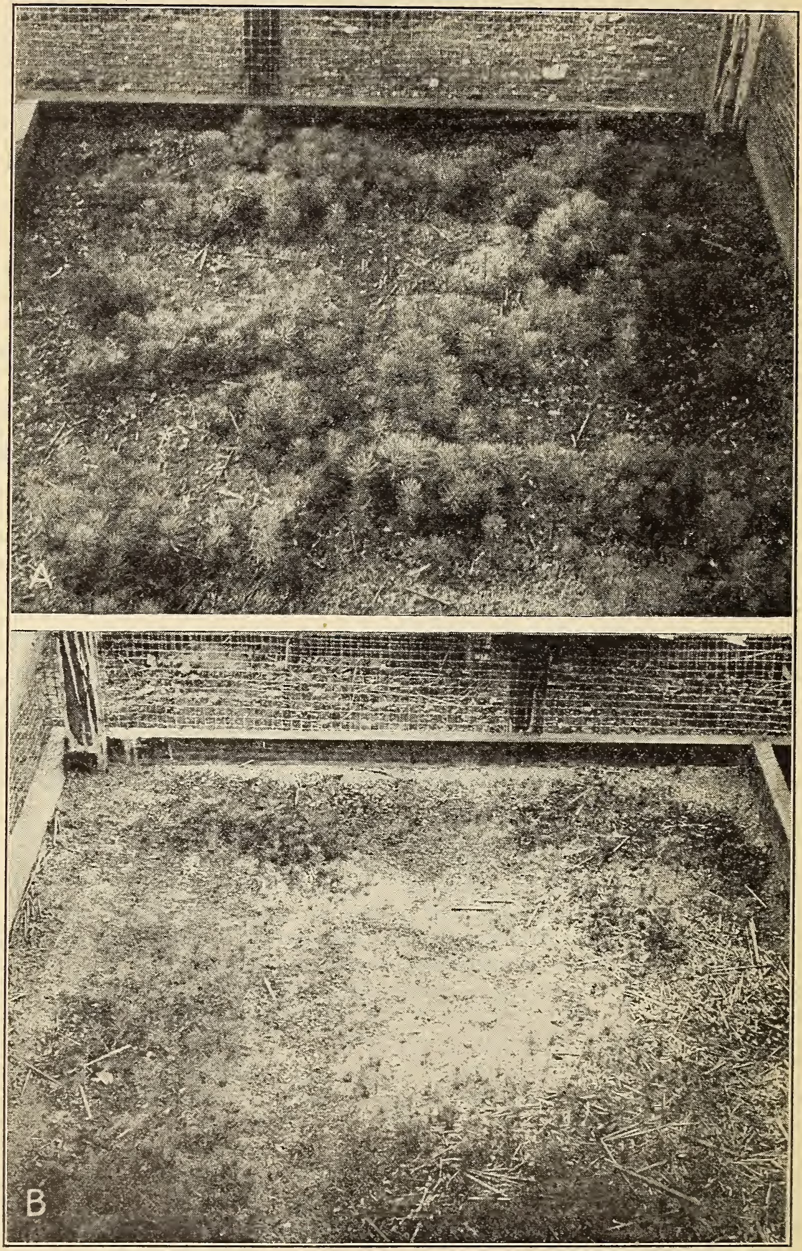

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FIGURE 1.—FERTILIZATION WITH SHEEP MANURE

Comparison of 2-year-old Engelmann spruce seedlings growing on soil fertilized (A) with sheep manure at the rate of 30 pounds per bed of 48 square feet, and (B) on unfertilized soil

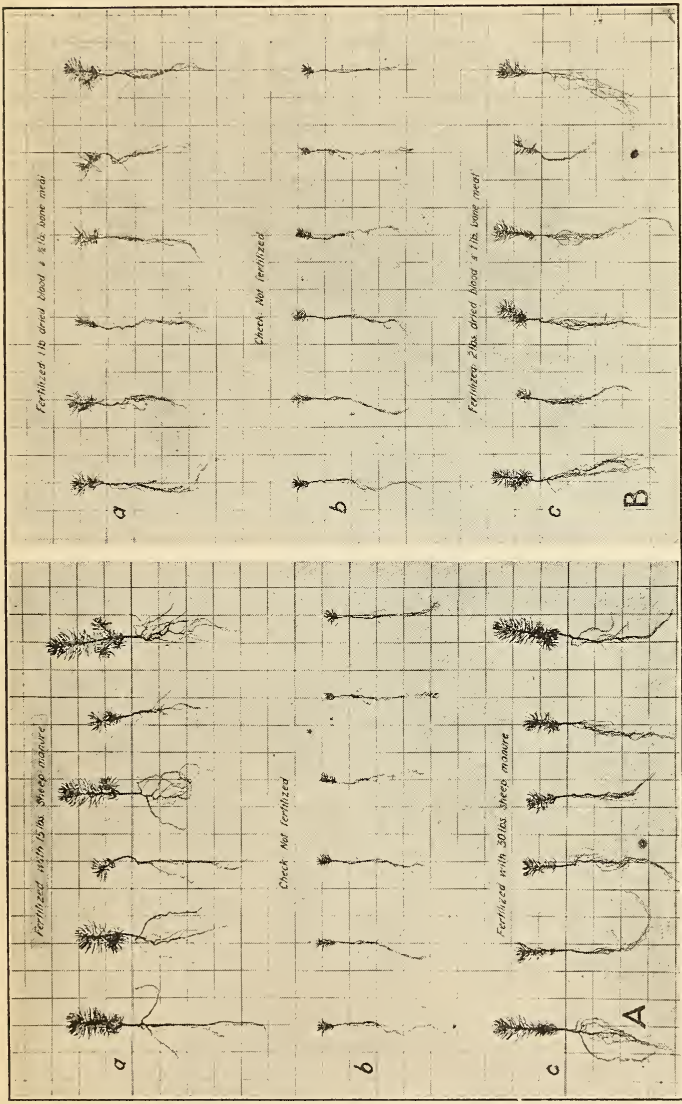

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FIGURE 2.—SHEEP MANURE AND BLOOD-AND-BONE FERTILIZER CONTRASTED

Two-year-old Engelmann spruce seedlings fertilized with light and heavy applications of (A) sheep manure and (B) 2–1 blood and bone compared with check-plot specimens. *a*, The result of light application; *b*, no fertilizer; *c*, of heavy application

The 3–0 fertilized seedlings, in most cases, were much taller and more than twice as heavy as the 3–0 seedlings grown on unfertilized soil. These 3-year-old trees seemed to have developed better in every way on fertilized soil than on unfertilized soil, except for a slightly greater top-heaviness of the fertilized trees. This poor "balance," as it is usually called, appears to be characteristic of seedlings grown in fertilized soil, being observed at Wind River and other forest nurseries. Development of both tops and roots is increased by fertilization, but increases in top growth are greater. However, if this top-heaviness is not unduly increased by too severe pruning of roots at the time of planting, it may not be so significant for spruce as it was found to be for western yellow pine in earlier experiments (*37*).

The 4–0 unfertilized seedlings had larger numbers of short primary lateral rootlets than most of the 3–0 fertilized seedlings, but in total numbers of rootlets and in all other characteristics studied, they too were surpassed by the younger fertilized seedlings. Thus it appeared that unless fertilization had decreased the hardiness of the trees, more than a year's time had been saved in the period necessary for nursery culture of seedlings.

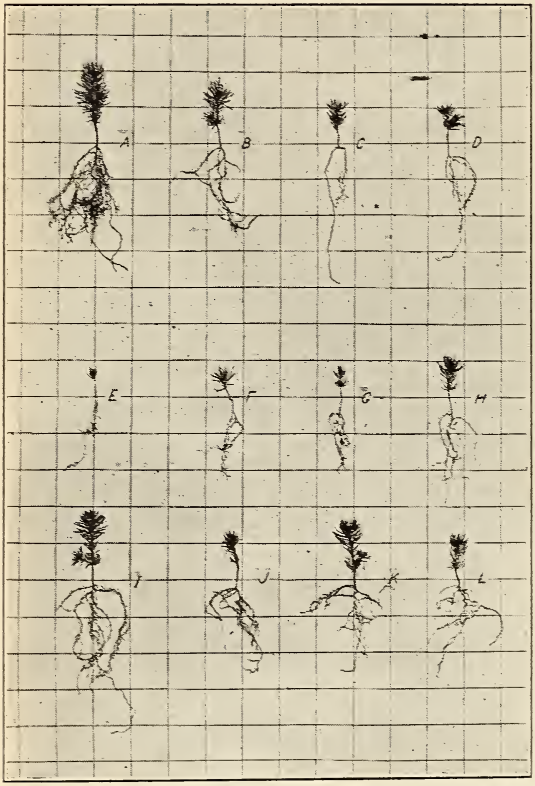

FIGURE 3.—EFFECT OF FERTILIZED SOIL ON 2-0 ENGELMANN SPRUCE SEEDLINGS

A, 30 pounds of sheep manure per 48 square feet; B, 15 pounds of sheep manure; C, 1 pound dried blood, 3 pounds bone meal, 16 pounds wood ashes; D, one-half pound dried blood, 1½ pounds bone meal, 8 pounds wood ashes; I, 1 pound dried blood, 2 pounds ground bone; J, one-half pound dried blood, 1 pound ground bone; K, 2 pounds dried blood, 1 pound ground bone; L, 1 pound dried blood, one-half pound ground bone. Seedlings E–H were not fertilized

Another series of observations was made to compare transplants from fertilized and unfertilized seed beds. In the spring of 1923 about one hundred 2-year-old seedlings were transplanted from each of the six differently treated lots sown in 1921. None of the trees

died as a result of this move, but growth was negligible during their first year in the new location. At the end of the following year the height of each 2–2 transplant was measured. The average heights of plants that had been normally watered in the seed beds were: Unfertilized 2.56, lightly fertilized 2.52, and heavily fertilized 3.19 inches. The plants that had been heavily watered in the seed beds showed a more regular gradation of height in the transplant rows, as follows: Unfertilized 2.55, lightly fertilized 2.96, and heavily fertilized 3.16 inches. Heavy watering slightly increased the height of only those transplants that were lightly fertilized as seedlings. Obvious although unmeasured differences in the trees when they were 2–0 seedlings have been described in the first paragraph of this section. These differences, resulting from fertilization of seed beds, persisted to a lesser degree two years after transplanting in unfertilized nursery soil. Final judgment as to the relative values of the different methods of culture was reserved until the results of field-planting tests with both seedlings and transplants were known.

TABLE 2.—*Relative anatomical development of 0–3 and 4–0 Engelmann spruce seedlings under different degrees of watering and fertilization*[1]

Treatment	Age class	Basic number of plants	Height of stem	Diameter of stem	Primary lateral rootlets[2]		Secondary lateral rootlets[2]		Total lateral rootlets	
					Short, 0.5 to 2 inches	Long, 2 inches or more	Short, 0.5 to 2 inches	Long, 2 inches or more	Short	Long
		Number	*Inches*	*Millimeters*	*Number*	*Number*	*Number*	*Number*	*Number*	*Number*
Heavily watered:										
Heavily fertilized	3–0	110	2.78	1.65	5.27	6.18	7.70	1.75	12.97	7.93
Not fertilized	3–0	110	1.64	1.02	4.55	3.17	1.44	.33	5.99	3.50
Do	4–0	110	1.95	1.23	6.33	4.61	2.60	.38	8.93	4.99
Lightly fertilized	3–0	110	2.78	1.59	5.44	5.59	6.44	1.70	11.88	7.29
Normally watered:										
Heavily fertilized	3–0	82	2.69	1.68	6.07	4.72	4.85	2.10	10.92	6.82
Not fertilized	3–0	110	1.76	1.14	6.05	4.28	1.92	.32	7.97	4.60
Do	4–0	110	1.98	1.21	6.57	3.95	1.92	.23	8.49	4.18
Lightly fertilized	3–0	107	2.18	1.40	5.63	5.43	7.32	1.71	12.95	7.14

Treatment	Age class	Oven-dry weight of plant	Percentage of weight in tops	Percentage of weight in roots	Stem growth in 1923
		Gram	*Per cent*	*Per cent*	*Inches*
Heavily watered:					
Heavily fertilized	3–0	0.468	68	32	1.56
Not fertilized	3–0	.179	64	36	.84
Do	4–0	.273	66	34	------------
Lightly fertilized	3–0	.490	71	29	1.37
Normally watered:					
Heavily fertilized	3–0	.535	69	31	1.59
Not fertilized	3–0	.238	65	35	.82
Do	4–0	.259	63	37	------------
Lightly fertilized	3–0	.383	65	35	1.27

[1] The figures in Table 2 are based on representative plants from the beds sown in the spring of 1921. These were fertilized with blood and bone mixed in the ratio of 1 to 2. Of this mixture the heavily fertilized plots received 3 pounds and the lightly fertilized plots 1½ pounds per bed of 48 square feet. The heavily watered plots received 69 per cent more water than the normally watered plots.

[2] Branches from the main central or tap root are called primary lateral rootlets while the branches of lateral roots are called secondary laterals.

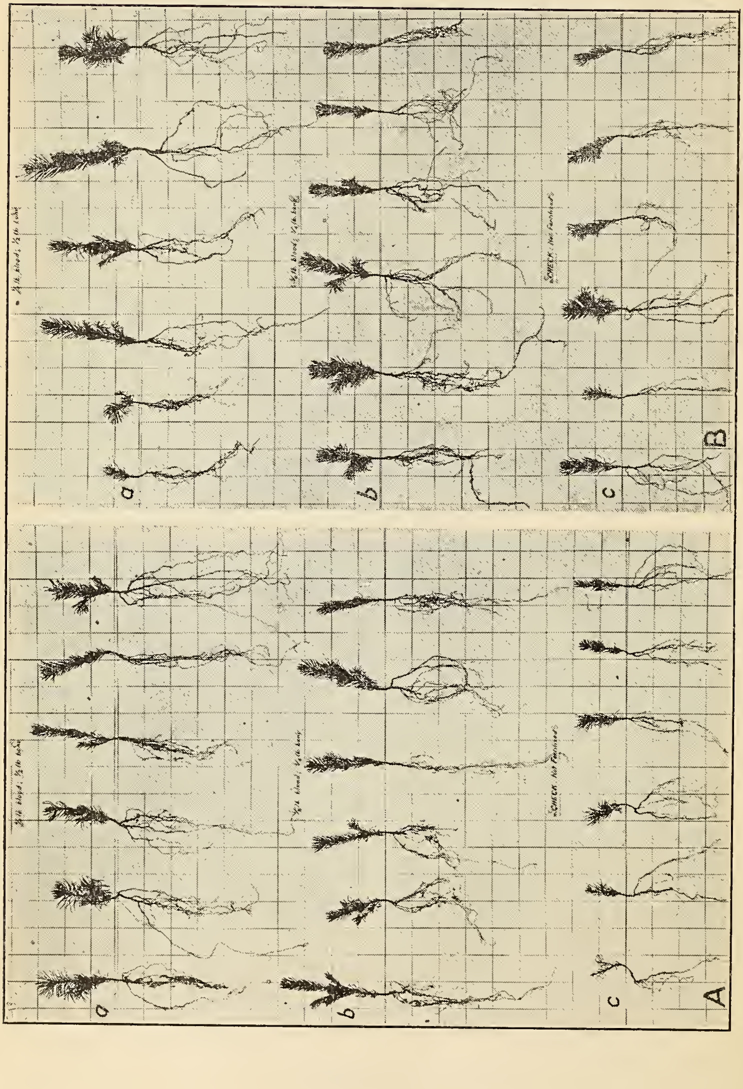

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FIGURE 4.—EFFECT OF WATERING ON SEEDLINGS

Three-year Engelmann spruce seedlings: A, Heavily watered; B, normally watered. Seedlings in upper row, *a*, are from plots fertilized with 1 pound dried blood and 2 pounds ground bone per bed of 48 square feet; *b*, similarly treated with one-half strength; *c*, from unfertilized check plot

SURVIVAL IN THE FIELD

The first field plantation was established under favorable weather conditions in the fall of 1923. The stock consisted of 3–0 spruce seedlings grown in the beds sown in the spring of 1921. All roots were pruned to a length of 7 inches.

Although no differences in behavior of the trees as shown in Table 3 are traceable to the amount of water applied in the nursery, the effect of fertilization in increasing thrift and survival stands out clearly. Differences in plant vigor as evidenced by thrifty color of foliage may have been less responsible for these results than were the differences in size and development of the seedlings. This was because of the extensive injury to the smaller plants from sliding soil as described in an earlier paper (*36*). The partial or complete burying of many of the small plants definitely contributed to the low survival of the unfertilized seedlings as a whole. Nevertheless, drought seemed to be the major cause of death. The period of growing months from April to August, inclusive, was abnormally dry during both 1924 and 1925 and caused heavy losses from all lots of planted trees. Most of these losses (68 to 79 per cent) occurred, however, during the first year after planting. Apparently this was due partly to the fact that according to local records about 1.3 inches more rain fell during the growing period of 1925 than in 1924, and partly to the shock that always results from field planting. Frost, which sometimes nips spruce seedlings badly, injured 1 per cent or less of the seedlings in each lot.

TABLE 3.—*Condition two years after field planting of 3–0 Engelmann spruce seedlings grown under various seed-bed treatments in the nursery*[1]

Treatment in the nursery	Basis, trees	Condition of trees				Injured but not killed by sliding soil
		Thrifty	Unthrifty	Alive	Dead	
	Number	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
Heavily watered:						
Heavily fertilized	300	46	1	47	53	4
Lightly fertilized	300	36	2	38	62	6
Not fertilized	600	26	1	27	73	16
Normally watered:						
Heavily fertilized	234	46	3	49	51	4
Lightly fertilized	300	33	1	34	66	9
Not fertilized	597	25	1	26	74	12

[1] In the nursery these seedlings were fertilized with dried blood and ground bone in 1 : 2 ratio. Of this mixture the heavily fertilized plots received 3 pounds and the lightly fertilized plots 1½ pounds per bed of 48 square feet. The heavily watered plots received 69 per cent more water than the normally watered plots.

A similar plantation of 2–2 transplants was made in the spring of 1925. As these trees remained only two years in the fertilized plots where the 3–0 seedlings were produced they were exposed to the benefits of rich soil for a shorter period. This was followed by two years in unfertilized transplant rows where, owing to favorable conditions of soil moisture and tilth, the trees originally from unfertilized check plots partially caught up with the others. Consequently the field planting was done with more uniform material leading to less significant contrasts in survival. Nevertheless, the results served to corroborate the beneficial effect of fertilizers as shown in the plantation of 3–0 seedlings.

SODIUM NITRATE SOLUTION AS A TOP-DRESSING

Another phase of the stimulation of Engelmann spruce growth in the nursery deserves consideration. Because the seeds are very small it is always difficult to broadcast them uniformly in the beds, and numerous overdense patches of seedlings are certain to result. Also stands of spruce seedlings are typically irregular because of such factors as variation in size of seeds, inherent differences in individual plants, and local variations of soil. Deficiency of soil nitrogen produces numerous patches of puny yellowish seedlings which frequently coincide with the overdense patches where competition is keen. In so far as low soil fertility was responsible for the undesirable irregularity in seed beds, it was thought that top-dressings on the worst spots might be found beneficial. A solution of sodium nitrate was chosen for tests of the efficacy of top-dressings.

In the spring of 1924 solutions of sodium nitrate in different strengths were applied to 4 by 12 foot beds of slow-growing 2–0 spruce seedlings. Samples of the dry salt weighing respectively 0.1, 0.5, 1, and 2 pounds each were dissolved in 3 gallons of water and distributed by a sprinkling can over 48 square feet of surface. The location of patches of yellowish trees was mapped in order to facilitate observation of results. The bed receiving the heaviest application of the chemical contained a large number of these inferior yellowish trees. Many of the poorest trees in this bed were killed by a heavy frost on May 25, four days after the treatment. The same frost nipped the new growth on one-half to three-quarters of all spruce seedlings. After five months of ordinary nursery care the yellowish foliage had almost completely turned green in all the treated beds, except the one that received only 0.1 pound of nitrate. This lightest application was apparently of some little benefit because the yellow foliage had slightly improved in color and growth was somewhat accelerated. On the other hand the heavy application of 2 pounds of nitrate killed the weaker plants and injured otherwise healthy green plants.

Many thrifty dominant seedlings in the heavily treated bed developed wholly unnatural yellowish tips on the needles, quite unlike the usual yellowishness mentioned as a result of poor soil. In this fatal scorching of foliage the sodium nitrate, like other strong solutions of salts, seemed to act directly on the leaf tissues, withdrawing water from the cells with which it remained in contact and killing them by plasmolysis. The 1-pound and the 0.5-pound applications showed very little evidence of such scorching and appeared to have been of much benefit. They not only corrected the color of needles but yielded marked increases in growth.

In the spring of 1925 two more trials were made to check the results of the previous year and to test the treatments on a younger age class. No field tests were made with any of the seedlings. This time 1-year-old seedlings were treated with sodium nitrate solutions at the rate of 1 and 2 pounds of salt per bed of 48 square feet. The heavier dose killed or severely injured about one-third of the plants. These were the smallest and weakest seedlings in the beds. Several of the dominant individuals showed slight signs of injury to the tips of needles from plasmolysis. The lighter application killed

only about one-tenth of the plants in the bed and these were all very small seedlings. Several medium-sized plants showed slight signs of injury, but all dominants remained very thrifty.

Increases in growth were slight and, as in other fertilizer trials, were not in evidence until the second year, even though the fertilizer used was in readily soluble form. During its first year a tree seedling naturally expends much energy in root development at the expense of top growth. After having spent a year developing roots it seems better able to absorb soil nutrients and use them for further growth of the seedling as a whole, especially for top growth. Thus in nursery work it would seem best to apply sodium nitrate in solution as a top-dressing on seedlings 2 years old or older if increased growth is the object sought. Much of the fertilizer applied to 1–0 stock is lost by leaching before it can become effective. On the other hand, if thinning out of weak and crowded individuals is the main object, the application may well be made on the poor spots in 1–0 stands where the inferior seedlings occur. In most cases in actual practice both objects deserve consideration and could be met by early spring applications of suitable quantities of sodium nitrate on 2-year-old seed beds. Hall (*11*) recommended that sodium nitrate be used only as a top-dressing because of its very rapid percolation through the soil.

SUMMARY OF EXPERIMENTS WITH ENGELMANN SPRUCE

Except on heavily fertilized plots, unusually heavy watering of Engelmann spruce seedlings for three years in the nursery had some tendency to produce large stock with a larger top-root ratio, but it had little effect on height of 2–2 transplants, and no significant effect on survival of 3–0 stock in the field.

Fertilization with dried blood and bone meal had a marked effect on growth. In spite of somewhat larger top-root ratios, the superior development of fertilized 3–0 seedlings enabled them to survive field planting in greater numbers than the unfertilized plants of the same age. These smaller unfertilized plants suffered relatively more from the action of both sliding soil and drought. Heavily fertilized 3–0 seedlings, particularly those not heavily watered, were found to be almost twice as large, by weight, as similar 4–0 unfertilized seedlings. The same was true of lightly fertilized and heavily watered 3–0 seedlings, whereas the lightly fertilized and normally watered seedlings were half again as heavy as the year-older unfertilized trees. These differences, together with increased height, made the fertilized trees much easier to handle in planting work. It appeared that at least a year[4] has been saved on the 5 and 6 year periods formerly necessary for the production of suitable planting material.

A few tests indicate that sodium nitrate in solution in quantities of 0.5 or 1 pound to 48 square feet may be advantageously used as a top-dressing for 2–0 spruce beds in order to eliminate the weaker and crowded individuals and force the growth of the better trees.

[4] As the survival of the 3–0 stock was not entirely satisfactory, 4–0 fertilized seedlings are recommended for field use.

LATEST EXPERIMENTS TO MAINTAIN SOIL PRODUCTIVITY

THE NEED FOR INCREASED FERTILIZATION

The latest experiments with fertilizers at Savenac Nursery were started principally for the purpose of finding adequate means for building up soil values that during the past few years have given evidence of deterioration. For 15 years or more intensive cropping has been practiced and during this time successive crops of seedlings have been grown at densities of about 100 per square foot of space. Furthermore, from these crops no roots, of course, were left in the ground as roots of agricultural crops often are. Despite the use of some dried blood and ground bone as fertilizers, and the plowing under of field peas every three or four years, the quality of the trees appeared to be declining.

One theory was that the much-discussed and little-understood soil toxins were causing lowered productivity. Palladin and Livingston (*23, p. 99*) state that soil frequently contains toxins although they are not generally excreted as such from plant roots. Microorganisms may play an important part in the production of toxins from organic material. Fortunately the deleterious effects on soil can often be removed by oxidation or by the addition of proper substances. Waksman (*38*) states that certain metabolic products are formed by at least some soil microorganisms, which are either toxic to themselves or to other organisms, and that the removal, destruction, or modification of these products may bring about an increased activity of the microorganisms concerned. According to Hutchinson (*17*) organic matter decomposing under anaerobic conditions due to water-logging, may result in the formation and deposition of waxes and slimes on soil particles, tending to block up their pores, interfere with aeration and drainage, and to protect the organic particles from further bacterial action. These phenomena might result from excessive irrigation of nursery soil, although the present deficiency of soil organic matter at Savenac might prevent such action. Clements (*5*) concludes his work on aeration and air content with the statement that—

> organic toxins are excreted by roots or produced in soils only as a consequence of the anaerobic respiration of plant roots and of microorganisms, and that inorganic toxins may arise as a result of chemical processes or of adsorption.

Similarly in his monograph on soil conditions Russell (*24, p. 153*) states:

> There is no evidence of the presence of soluble toxins in normally aerated soils sufficiently supplied with plant food and calcium carbonate, but toxins may occur on "sour" soils badly aerated and lacking in calcium carbonate, or on other exhausted soils.

A strongly acid condition (pH value about 5.3) was detected at Savenac Nursery and corrected by the use of lime, but this alone did not appear to solve the problem.

Another theory of the lowered productivity of the nursery was soil exhaustion, but, in the strict sense of this term as used by agronomists, this is impossible in virgin soil during any period so short as the present age at Savenac Nursery. An initial deficiency of available nitrogen in the soil is not surprising, because much of

the original supply was probably lost to the atmosphere in the forest fire that preceded establishment of the nursery and in the later fires used in clearing the land. The subsequent drain on soil nitrogen as a result of cropping obviously exceeded the small additions of this element in available form through rain water, leguminous cover crops, and light fertilization. Failure to maintain soil organic matter in adequate amount has been a fundamental weakness in the local soil management. It is probable that intensive cropping has been removing readily available nutrients at a faster rate than that at which they naturally become available from soil reserves by the gradual process of weathering. Such a condition would become manifest in much the same symptoms as those of soil exhaustion. The obvious remedy is either a reduction in the intensity of cropping or an increase in the intensity of fertilization.

European nurseries depend to a large extent upon compost in which manure, weeds, forest litter, and various organic waste materials are decomposed.[5] It is agreed that such fertilizer is desirable for Savenac nursery in as large amounts as can be readily obtained locally. If the physical condition and humus content of the soil can be maintained by these means, the permanent productivity of the soil could doubtless be preserved with very little or no use of the more concentrated and chemical fertilizers. It is unlikely, however, that such bulky material can be made locally available in adequate quantity at reasonable expense. As in agriculture, there will probably always be a place in forest-nursery practice for the commercial fertilizers. Not long ago Beaumont[6] pointed to the increasing use of high-analysis fertilizers, and Whitney (*39*) recently predicted expansion in the general use of such concentrated fertilizers as ammonium nitrate, ammonium phosphate, potassium phosphate, and potassium nitrate. Such materials, devoid of commercial fillers, can be shipped cheaply and in use they may be combined, if necessary, with local supplies of more bulky humus-yielding materials.

Nitrogen, phosphorus, and potassium are common elements in fertilizers because they are of primary importance in plant life and are often deficient in cultivated soils. Calcium, magnesium, iron, and sulphur are less commonly used in fertilizers because they are present in adequate quantity in soil. According to a microscopic examination of samples of soil from Savenac Nursery made by the Bureau of Soils in 1921, minerals that should yield potash slowly under the process of weathering, namely, potash feldspar (orthoclase and microcline) and potash mica (muscovite and biotite), were fairly

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[5] It is understood that many European nurseries maintain three compost heaps in different stages of decomposition. Each year material from the oldest one is applied to the land as fertilizer. One of the objects of composting is the reduction of carbon content, through the loss of carbon dioxide to the atmosphere, and a corresponding increase in the percentage of contained nitrogen. A similar loss of nitrogen by the escape of ammonia fumes to the air is to be avoided. Thorne (*30*) found that the addition of 30 per cent of marl reduced the loss of nitrogen to 10 per cent. The addition of from 2 to 5 per cent of peat or of sodium bisulphate still further reduced the loss. Similar results are claimed for gypsum which is supposed to be decomposed by the manure with the formation of the comparatively stable compound sulphate of ammonia. In general there is less loss from manure when leaching is prevented and the manure is thoroughly tamped by animals. The manure piles should be sheltered from rain and consequent leaching. About half of the plant food is in a liquid form which keeps the material moist, and which is best conserved by the use of a concrete basin for the compost.

[6] BEAUMONT, A. B. THE USE OF CONCENTRATED FERTILIZERS. Mass. Agr. Expt. Sta. Circ. 72, 3 p. 1925. [Mimeographed.]

plentiful, especially the former. Although no phosphates or carbonates of calcium were noted, lime-soda feldspars (plagioclases) were present in all samples. No quantitative analysis of soil nutrients was made. The value of such artificial tests is small (*8*) because it is assumed that plants absorb chemicals from the soil in the same way that the laboratory reagents do. This is not a safe assumption, and it has been recommended in German nursery practice that such analyses be entirely replaced by field experiments.

THE TRIANGLE EXPERIMENT

With the selection of sodium nitrate as a source of nitrogen, superphosphate (acid phosphate) as a source of phosphorus, and muriate of potash as a source of potassium, an experiment was planned to show in what proportions these materials should be mixed in order to obtain the most favorable growth response in tree seedlings.[7]

Twenty-three plots of 3 square feet each were sown in May, 1925, with Engelmann spruce seed collected on the Lolo National Forest in 1923 and western yellow pine seed collected the same year on the Bitter Root National Forest. Half of each plot was sown with 2.312 grams or approximately 1,000 seeds of Engelmann spruce, and the other half was sown with 26.97 grams or approximately 500 western yellow pine seeds. Wooden frames extending 8 inches into the soil surrounded each plot and a lath shade was provided for the half in which spruce was sown. Significant results have been attained thus far only with the western yellow pine and the following discussion is therefore confined to observations of that species. A triangular arrangement of 21 fertilized plots was employed to facilitate a study of the effect of three variables in various combinations. The principle is that first used by Schreiner and Skinner (*25*, *26*) and later employed by Shive (*27*). Guided by the results of numerous agricultural experiments at various stations, a range of applications of each chemical was so selected for testing as to include what seemed likely to be the most effective treatment. Sodium nitrate was tested in amounts varying from 160 to 800 pounds per acre, superphosphate from 80 to 400 pounds, and muriate of potash from 30 to 150 pounds per acre. As shown by the figures on Figure 5, the plots were so arranged that the heaviest application of each material was used alone in each corner plot, whereas all other exterior plots were treated with various proportions of two materials, and the interior plots received different mixtures of all three fertilizer materials.

The quantity of each of the three fertilizers used in any one plot was determined by the relative position of that plot in the triangle. The farther any plot was removed from a certain corner of the triangle, the less it received of the fertilizer represented at that corner. Two unfertilized check plots were located near the test plots but outside of the triangle.

Precautions were taken to insure that the plots received equal quantities of water in sprinkling. Otherwise they were given ordinary nursery care. Views of the plots are shown in Figure 6.

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[7] Fletcher (9) indicates that, unlike some of the common fertilizer ingredients, these materials may be safely mixed at any time before they are applied to the soil. Incidentally Fletcher's article should be found useful to nurserymen in computing nutrient values and fertilizer formulas expressed in pounds per acre when local mixtures are being made up.

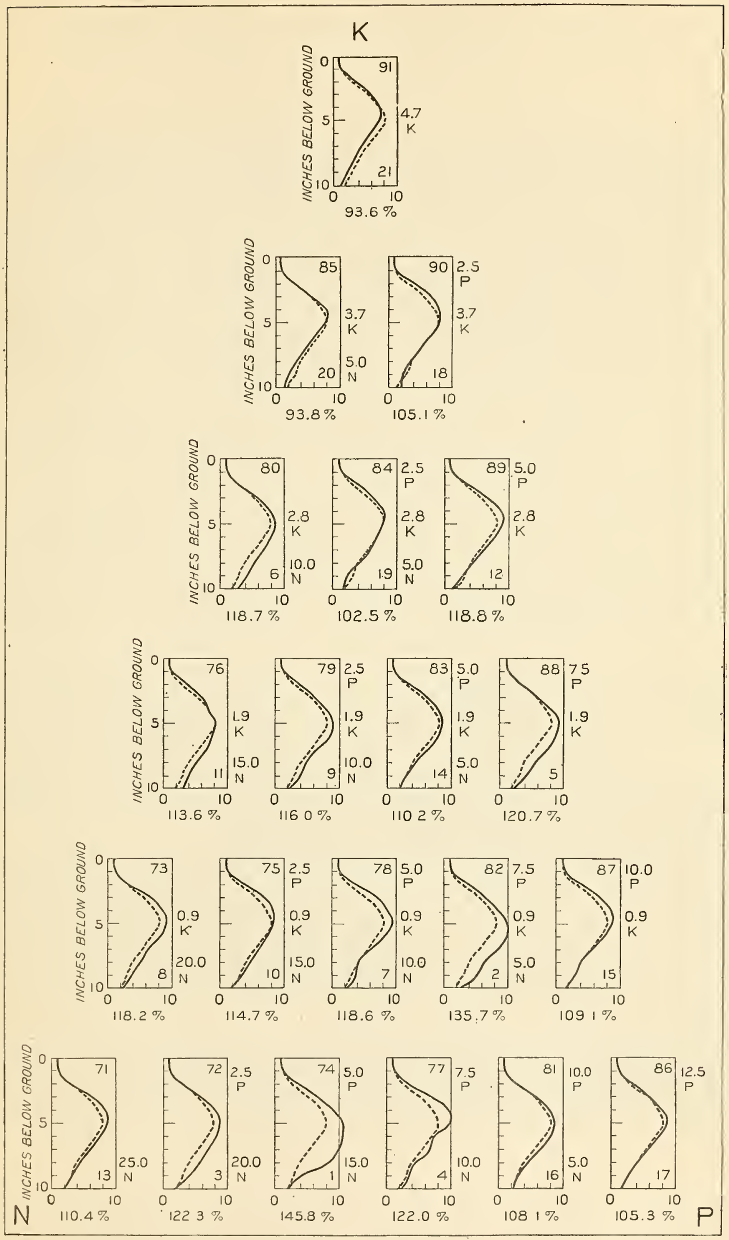

FIGURE 5.—Curves of root frequency distribution in the triangle experiment. Average number of rootlets is shown on the horizontal scale. The dotted line represents the average of two unfertilized check plots; each solid line represents one test plot fertilized as shown by figures at right. The number at upper right of rectangle is the plot number; that at lower right indicates the rank of each plot in area of root surface. This area of root surface, as compared with check plots, is shown by the percentage figure below each rectangle

The plots exhibited no striking differences in the progress of germination and loss during the first season. The following fall all the 2–0 western yellow pine seedlings were removed and from them were selected those that were considered sufficiently developed for field use. From among the better seedlings 50 representatives from

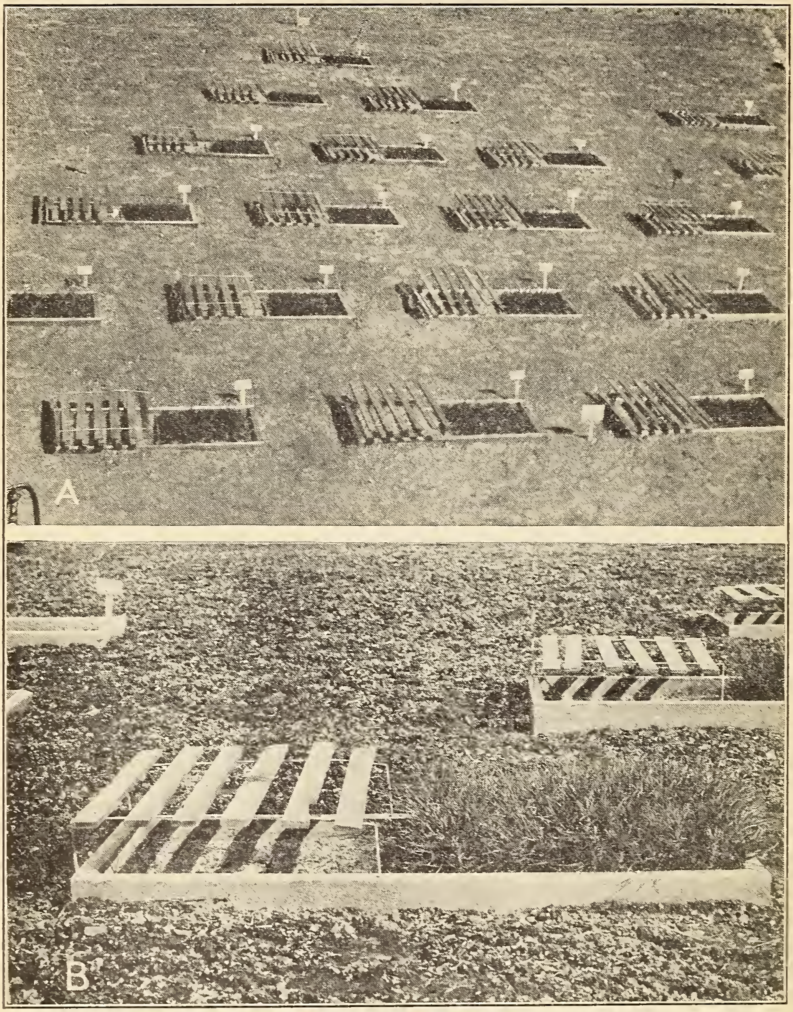

FIGURE 6.—THE TRIANGLE FERTILIZER EXPERIMENT

A, General view of the plot layout; B, near view of the test plots. The Engelmann spruce seedlings under the lath shade are too small to show in the picture, but the 2–0 western yellow pines in the unshaded portion grew rapidly and are conspicuous

each plot were subjected to detailed measurements. In addition to measurements of heights and diameters of stems, the numbers of rootlets found at regular intervals from the ground line were counted. These counts were made across the whole root system at points 1 inch apart, and to a depth of 10 inches. Thus each rootlet was

counted roughly as many times as it extended inches in length. The total number of 1-inch root segments multiplied by a constant (k=40 square millimeters, the estimated area of an average root segment 1 inch long) represent the approximate surface area of the roots, or the absorbing root surface. The unit of measurement, however, is less important than the segregation of averages for the different depths to show the vertical distribution of absorbing surface. As has been shown by other experiments in this region, a relatively large number of rootlets between the depths of 4 and 8 inches directly increases the ability of the tree to survive in the field. Figure 5 shows the curves of root frequency distribution for each plot. Apparently muriate of potash had no significant beneficial effect on root frequency, and the best results were obtained from plot 74. However, no conclusions can be drawn until the influence of the fertilizers on other parts of the plant has also been considered.

When root frequency counts had been completed in the laboratory, all seedlings were cut in two at the ground line, and the masses of tops and of roots from each plot were oven dried separately.[8] Thus not only the total dry weight of plant, but also the percentage of this weight contained in the root was determined for the average good plant from each plot. These data are presented in Table 4 as percentages.

For each plant quality or characteristic that was considered, the average measure of development attained in the two check plots was taken as 100 per cent to serve as the basis of comparison. Thus the different characteristics of the seedlings, originally measured in different terms and units, were expressed in uniform terms of percentage in order to make possible the average ratings given in the last column of Table 4.

It may be seen from the table that without exception the fertilizer treatments, as in the earlier experiments, were detrimental to good balance, top-heaviness having been invariably increased by fertilization. This is in accord with the work of Harris (*13*), who found that fertilizers reduced the relative root growth of wheat. Similarly it may be seen from the germination rating that in many cases fertilization apparently decreased germination or increased the early loss of seedlings. In all but one plot the yield of good 2–0 plants was also less. On the other hand, the fertilizers were distinctly beneficial to the general development of the trees.

In Table 4 more space is given to the development of roots than to that of tops or any other characteristic. This was purposely done in order to give in the last column what are, in effect, weighted averages based on all the measurements but with especial emphasis on root development.

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[8] The seedlings were dried in an electric oven until they ceased to lose weight. Relative humidity in the oven when the trees were removed was computed to be 0.7 per cent for the first batch and 0.6 per cent for the second batch. Computations were based on a formula by Professor Schallenberger, of the University of Montana, which reads: "Relative humidity in the oven equals relative humidity of the room (at temperature t) times pressure of saturated vapor (at temperature t) over pressure of saturated vapor at oven temperature t'." These computations would not have been necessary to the experiment had it been possible to dry all of the plant material in one batch. Psychrometer tables in a Weather Bureau publication (*33*) were used.

TABLE 4.—*Relative rating of different fertilizer treatments according to their effect on 2–0 western yellow pines, 1925–26, at Savenac Nursery*

Plot No.	Fertilizer treatment [1]: Sodium nitrate ($NaNO_3$)	Fertilizer treatment [1]: Superphosphate (acid phosphate) ($CaH_4(PO_4)_2$)	Fertilizer treatment [1]: Muriate of potash (KCl)	Relative rating of fertilized plots with respect to unfertilized control plots: Germination [2]	Good 2–0 stock	Height of top	Diameter of stem	Oven-dry weight	Balance [3]	Total root surface	Root surface 4 to 8 inches deep	Average quality rating
	Grams	*Grams*	*Grams*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
71	25	0	0	103.9	81.3	131.2	116.9	158.1	72.9	110.4	110.4	110.6
72	20	2.5	0	102.9	84.0	139.1	119.6	169.2	78.1	122.3	127.1	117.8
73	20	0	0.9	112.7	88.0	143.7	120.9	175.9	71.4	118.2	120.4	118.9
74	15	5.0	0	99.5	97.3	127.9	119.6	147.7	88.3	145.8	164.0	123.8
75	15	2.5	.9	95.6	88.0	139.1	120.3	171.8	77.6	114.7	111.7	114.8
76	15	0	1.9	110.8	85.3	161.9	127.7	213.5	67.4	113.6	113.3	124.2
77	10	7.5	0	96.6	74.7	161.4	134.5	236.3	67.4	122.0	116.5	126.2
78	10	5.0	.9	97.1	93.3	147.0	125.0	182.3	75.3	118.6	113.9	119.1
79	10	2.5	1.9	109.3	84.0	149.8	127.0	188.8	69.5	116.0	117.1	120.2
80	10	0	2.8	99.0	92.0	144.2	123.6	176.8	71.9	118.7	119.7	118.2
81	5	10.0	0	95.1	81.3	115.3	112.2	125.9	84.9	108.1	111.8	104.3
82	5	7.5	.9	95.1	88.0	156.3	132.4	229.8	70.3	135.7	143.3	131.4
83	5	5.0	1.9	96.1	102.7	124.7	113.5	138.2	85.9	110.2	111.1	110.3
84	5	2.5	2.8	96.6	81.3	129.3	109.5	134.4	76.6	102.5	102.0	104.0
85	5	0	3.7	109.3	70.7	109.8	98.0	119.5	83.1	93.8	91.5	97.0
86	0	12.5	0	90.7	88.0	106.5	97.3	97.4	96.6	105.3	107.5	98.7
87	0	10.0	.9	87.3	92.0	97.7	91.9	96.3	96.6	109.1	107.0	97.2
88	0	7.5	1.9	95.1	89.3	122.3	102.0	131.3	87.8	120.7	126.9	109.4
89	0	5.0	2.8	116.2	72.0	114.9	98.6	109.2	89.3	118.8	112.7	104.0
90	0	2.5	3.7	99.0	92.0	115.3	99.3	115.9	85.7	105.1	97.5	101.2
91	0	0	4.7	106.4	90.7	116.3	99.3	110.3	85.9	93.6	87.3	98.7
94 and 95	0	0	0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[1] The application of 25 grams of fertilizer to one of these test plots corresponds to 800 pounds per acre.
[2] Total stand of 1–0 stock.
[3] Percentage of weight in roots as related to balance in control plots.

Figure 7 indicates that the best results in general were obtained in that third of the triangle which was nearest the nitrogen corner. Judged from the top only, before the trees were lifted, plot 76 and plots adjacent to it appeared to contain the best trees in the whole triangular area. When the plants were excavated and root characters also were studied, plot 82 stood out as best of all. However, the location of this plot, on the edge of the group of best-developed plots, led to the suspicion that its excellent seedlings may have been due to some unknown extraneous influence. Hence more weight was given to plot 74, which was rated as best when account was taken only of root surface, the extent of which is one of the most important characteristics of planting stock. When plots 74 and 82 are con-

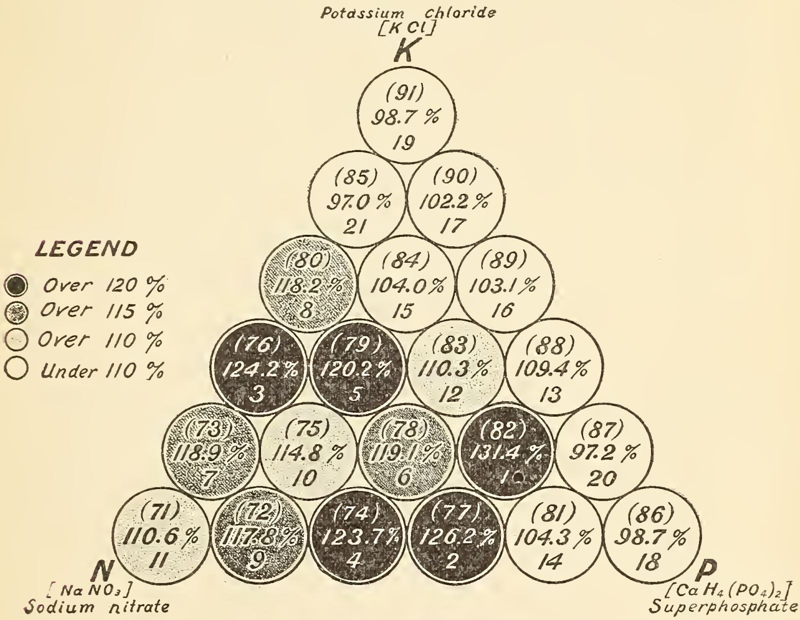

FIGURE 7.—Rating of results from the triangle experiment in quality of plants. Figures in parentheses are plot numbers; the lowest figures give the ranking order of the plots. Percentages are those shown in the last column of Table 4

sidered together with other controlling plots in the group, the center of best development seems to fall nearer to plot 78 than to any other. A more precise determination of this center is not possible from the available data, nor is greater precision necessary for practical application. The constant changes in fertility as a result of cropping make flexible fertilization formulas desirable. In view of this the following recommendation is made, based on the results of the triangle experiment: In general, 160 to 480 pounds of sodium nitrate, 80 to 240 pounds of superphosphate, and less than 30 pounds of muriate of potash per acre or no potash at all, are best for western yellow pine seedlings to be grown at Savenac Nursery under the present condition of soil fertility.

Chancerel (*4*) reports a detrimental effect from potassium salts on woody plants. A detrimental effect from the heavier applications

of muriate of potash was suspected in this experiment. At any rate the addition of potash did not seem to promote growth. This may have been because the soil already contained sufficient potassium rather than to any positive adverse influence. Even so it is possible that light fertilization with potash may be found locally advantageous in other ways. Basing his view on years of agricultural experiments in England, Hall (*11*) stated that potash makes plants more resistant to fungous attacks even where nitrogenous manuring is heavy. Mooers (*22*), in summarizing the results of 20 years of experimentation with a rotation of wheat and cowpeas, reported that although the yield of wheat was but slightly increased by potash manuring, the yield of cowpea hay showed an average annual increase attributable to potash of 633 pounds of cured hay per acre. The possibility of increasing the green fertilizer crop at the Savenac Nursery by some such means should be considered in further fertilizer experiments.

SIXTY SIMULTANEOUS FERTILIZER TESTS

The triangle experiment served its purpose in showing the approximate proportions of three common sources of nitrogen, phosphorus, and potassium to which western yellow pine responds best on Savenac Nursery soil. It did not show what source of these elements is most efficient in producing the most satisfactory planting stock. For this purpose a second series of experiments was established in the spring of 1925.

METHODS OF APPLICATION AND OBSERVATION

Suggestions as to the most promising materials to be tested were obtained from the early European work of Chancerel (*4*) on the effect of fertilizers on woody plants and from the results of numerous fertilizer studies at various agricultural experiment stations in the United States. Thirty common fertilizers, fertilizer ingredients, or mixed fertilizers were selected, each of which was to be tested in two strengths, a light and a heavy application, so chosen as to embrace the most probable best treatment. In general the heavy application was about twice the strength of the light one.

Each plot of 2 square feet was inclosed in a bottomless wooden frame and separated a foot or more from its neighbors. The fertilizers were thoroughly mixed by hand into the upper 5 inches of soil. On May 12, 1925, the plots were sown with *Pinus ponderosa* seed (collected on the Bitter Root National Forest in 1923) at the rate of 18.865 grams or about 350 seeds per plot, and covered with a ¼-inch layer of sand. The seedlings grown in these plots, like those in other tests of fertilizers, appeared to develop uniformly and seemed to be much like the unfertilized trees during the first year. During the second year marked differences occurred. Like the seedlings in the triangle experiment, they were given ordinary nursery care with precaution to ensure uniformity of watering. Likewise data were collected and compiled in the manner already described for the triangle experiment.

The fertilizers tested and the quantities used in the series of light applications are shown in Figure 8 which presents curves of root frequency distribution for each plot. The area included to the left of each curve represents the approximate total surface area of the

root system of the average seedling from each plot. Dotted-line curves showing the root development of unfertilized controls are

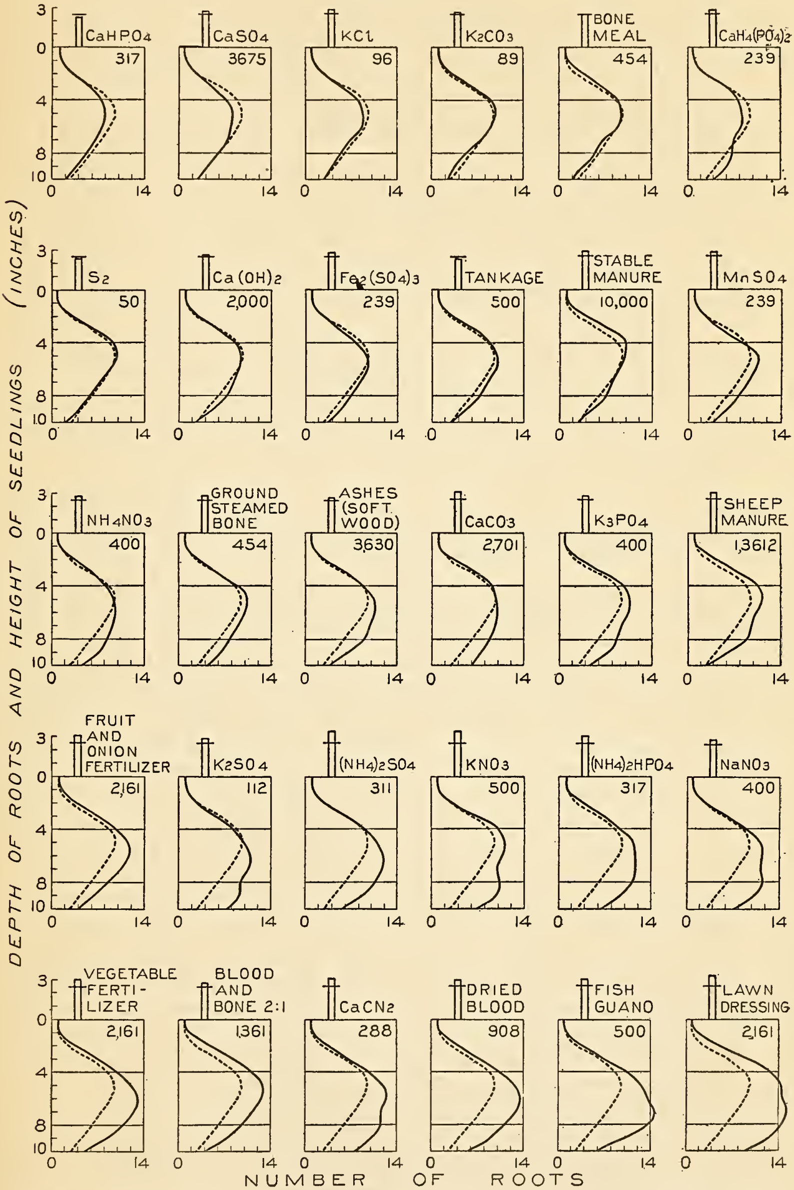

FIGURE 8.—Root frequency distribution and relative height of 2–0 western yellow pines grown on differently fertilized soil. Root frequency of fertilized plots as compared to the unfertilized check plots may be seen in a comparison of the solid curve with the broken-line curve; heights are similarly gauged by comparing column height (fertilized) with height of crossbar (unfertilized). Fertilizer mixture is indicated above each plot; just below is the figure for pounds per acre applied

included for comparison. The plots are represented in the order of magnitude of the response in total area of root surface.

Previous studies have shown that a relatively large absorbing root surface is desirable for forest planting stock, but that all parts of this surface are not equally effective. Summer drought causes the roots lying in the upper 4-inch layer of soil to be of relatively little help in promoting survival. The roots lying between 4 and 8 inches deep in the soil are in a moister medium where their benefit to the seedlings may be approximately proportionate to the extent of their surface area. This should be kept in mind when judging the fertilizer treatments on the basis of the results shown in Figure 8. Moreover all root systems are pruned to a total length of 8 inches just before planting. In the diagrams heavy lines have been drawn at the 4 and 8 inch levels in order to make it easier for the reader to visualize the location of the most effective root surface. Evidently the best results, judging from root surface alone, were obtained from the fertilizers carrying large quantities of available nitrogen. But root surface, although thought to be one of the most reliable anatomical characteristics on which to base judgments of quality of stock, is but one of several criteria. The general development of plants as indicated by weights of tops and roots, the height and thickness of stems, as well as the germination and yield obtained from seeds, are to be considered.

The method by which results from the triangle experiment were rated was used again in this experiment, with the results shown in Table 5. The fertilizer treatments have been listed in ascending order of their benefit to the seedlings, as indicated by the average rating figures. Nevertheless, the figures of individual characteristics entering into these average ratings may be equally worthy of consideration; also future experiments may be expected to improve our judgment as to the most suitable criterion. Readers disagreeing with the author's view that all of these characteristics are worthy of consideration in an average rating or that each has been given its proper relative weight, may compute an average rating that has been differently weighted in order to emphasize any desired quality. For instance, if seeds are cheap and little importance is attached to the rating of yield, its omission from the average rating would correspondingly increase the emphasis placed on plant development.

The ratings of four obviously important characteristics have been plotted in Figure 9. Each curve is based on one column of figures from Table 5 except the curve depicting yield. This is based on averages of the two columns in the table showing the total germination and the percentage of good 2–0 stock. A combination of these two may well represent potential yield. Consistent deviation below the horizontal base line at 100 per cent, representing the unfertilized controls, makes it clear that as a rule good balance is decreased by fertilization. This agrees fully with previous experience. General development, as indicated by total weight and to a lesser degree by root surface, was greatly increased by most of the treatments. Yield was moderately increased by fertilization.

TABLE 5.—*Relative rating of 30 different fertilizer treatments according to their effect on 2–0 western yellow pines grown in 1925 and 1926 at Savenac Nursery*

Plot No.	Fertilizer treatment: Material	Fertilizer treatment: Quantity per acre	Relative rating of different plots with respect to unfertilized control plots: Germination [1]	Good 2–0 stock	Height of top	Diameter of stem	Oven-dry weight	Balance [2]	Total root surface	Root surface 4 to 8 inches deep	Average quality rating
		Pounds	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
5	Calcium acid phosphate ($CaHPO_4$)	317	136.0	113.3	92.4	92.7	76.6	105.6	87.4	85.7	98.7
13	Flowers of sulphur (S_2)	50	115.4	120.0	95.8	93.9	85.7	104.5	100.5	99.0	101.8
11	Potassium carbonate (K_2CO_3)	89	116.9	118.3	103.8	91.5	89.5	101.4	97.8	96.8	102.0
21	Bone meal	454	100.7	133.3	102.9	95.2	97.3	98.6	98.4	95.6	102.8
12	Potassium chloride (KCl)	96	115.4	123.3	112.7	102.4	115.1	90.5	94.4	92.5	105.8
26	Tankage	500	112.5	126.7	95.8	93.9	99.4	99.7	109.3	109.1	105.8
9	Ferric sulphate ($Fe_2(SO_4)_3$)	239	104.4	110.0	112.7	109.1	112.8	94.7	104.3	106.8	106.8
2	Calcium hydroxide ($Ca(OH)_2$)	2,000	116.9	105.0	106.3	103.0	118.5	96.1	103.9	107.2	107.1
1	Calcium sulphate ($CaSO_4$)	3,675	105.9	133.3	110.1	114.5	111.2	96.9	92.5	94.2	107.3
4	Calcium superphosphate ($CaH_4(PO_4)_2$)	239	113.2	128.3	112.2	100.0	123.5	89.9	100.0	95.6	107.8
8	Manganese sulphate ($MnSO_4$)	239	114.0	120.0	112.7	106.7	117.8	88.2	113.4	118.8	111.4
25	Ashes (softwood)	3,630	108.1	113.3	109.7	100.6	122.8	97.5	122.0	126.0	112.5
24	Stable manure	10,000	111.8	141.7	119.4	106.1	123.4	87.4	112.9	106.8	113.7
14	Ammonium nitrate (NH_4NO_3)	400	122.1	131.7	112.2	105.4	115.2	98.9	115.9	114.2	114.4
23	Sheep manure	13,612	94.9	108.3	121.1	110.3	152.2	91.0	126.9	126.4	116.4
20	Steamed ground bone	454	116.9	126.7	116.9	114.5	143.4	95.2	116.9	116.7	118.4
16	Potassium phosphate (K_3PO_4)	400	114.7	135.0	115.6	106.7	136.7	91.3	124.7	123.6	118.5
30	Fruit and onion fertilizer	2,161	95.6	113.3	128.3	112.7	147.8	91.3	127.5	132.6	118.6
10	Potassium sulphate (K_2SO_4)	112	118.4	131.7	116.9	109.7	130.9	93.6	130.0	127.5	119.8
3	Calcium carbonate ($CaCO_3$)	2,701	110.3	118.3	125.3	125.5	159.4	89.4	123.2	116.9	121.0
22	Blood and bone (2 : 1 ratio)	1,361	78.7	131.7	113.1	120.6	161.3	94.1	145.1	143.6	123.5
6	Sodium nitrate ($NaNO_3$)	400	116.2	121.7	116.0	117.6	129.5	105.6	143.1	143.4	124.1
29	Vegetable fertilizer	2,161	102.9	115.0	125.3	113.3	158.6	92.2	144.4	151.4	125.4
18	Calcium cyanide ($CaCN_2$)	288	111.8	136.7	127.0	115.8	138.7	101.4	149.3	147.9	128.6
15	Ammonium acid phosphate ($(NH_4)_2HPO_4$)	317	88.2	143.3	127.8	126.1	168.5	94.1	142.1	142.8	129.1
27	Fish guano	500	94.9	136.7	121.1	114.5	143.3	94.4	161.6	169.5	129.5
7	Ammonium sulphate ($(NH_4)_2SO_4$)	311	114.0	113.3	140.5	126.1	186.3	83.2	136.6	141.1	130.1
17	Potassium nitrate (KNO_3)	500	116.2	138.3	138.8	125.5	165.7	87.7	137.8	132.3	130.3
19	Dried blood	908	101.5	153.3	121.9	119.3	162.0	97.8	153.1	156.9	133.2
28	Dia lawn dressing	2,161	89.0	121.7	135.4	127.3	218.3	89.6	184.3	181.6	143.4
31 and 32	No fertilizer	0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[1] Total stand of 1–0 stock.

[2] Percentage of weight in roots, as related to balance in control plots.

A possible relation between low germination or yield and good development is suggested by the fact that in Figure 9 the curve showing weight of plants rises or falls 23 times inversely as the curve depicting yield, whereas it proceeds in the same direction only 5 times.[9] Naturally, the development of seedlings in dense stands is inferior. In this experiment sowings were made relatively light in order to minimize the effect of variation in density as much as possible.

More definite comparisons of the effect of the different materials are desirable. The order in which these materials were arranged

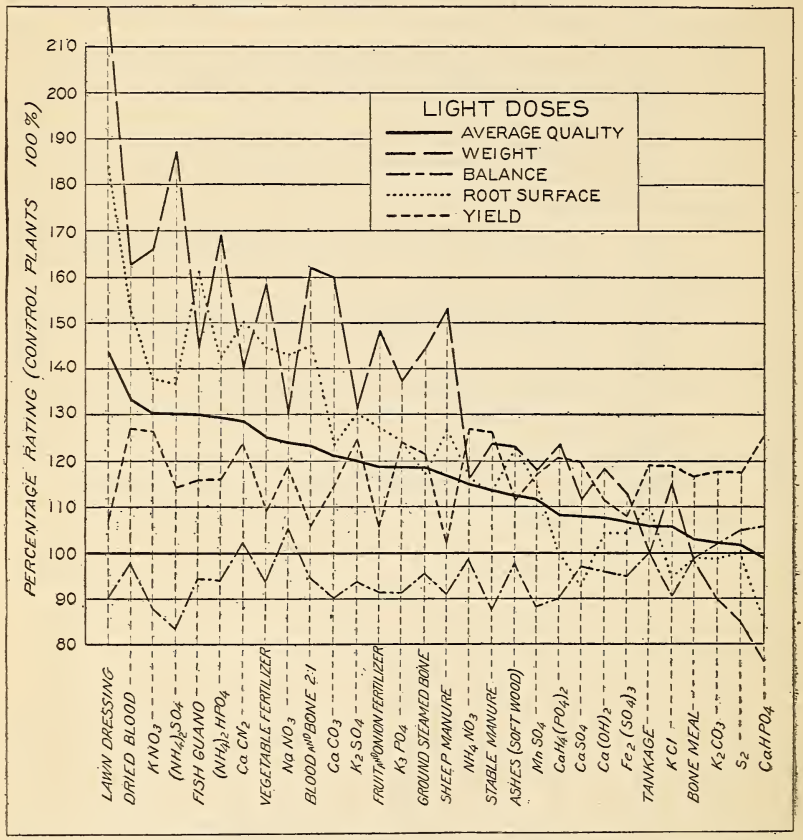

FIGURE 9.—Comparison of ratings according to average quality, weight, balance, root surface, and yield of 2–0 western yellow pines

in Figure 8, based on root surface only, was somewhat changed in Figure 9 and Table 5 where several other qualities were also considered. Because of its more comprehensive basis, the second order of arrangement is the more significant. Yet a further rearrangement becomes necessary when account is taken of the results of the heavy applications of the fertilizers, which were not included in

[9] By averaging ratings of balance with those of weight to obtain a better conception of general development, and by including the results of heavy applications also, curves of yield and development indicated a still closer inverse relationship. But the coefficient of correlation was only -0.26 ± 0.12, indicating a very weak and rather doubtful relationship.

the original scheme of rating because data on number and distribution of roots were not available. In some instances the heavier application represented the more efficacious use of a substance. In the absence of a wide range of trials of each fertilizer, the most effective quantities must remain undetermined, but it was possible in these experiments to select the better of the two applications tried in each case and then rank all the materials according to the results obtained from these better treatments. Such selection and ranking of the treatments was made on what appeared to be the best basis common to both series of plots, the lightly and the heavily fertilized.

Since the data on root counts could not be included in this common basis, the data on height and diameter of stems were omitted also in order to avoid giving relatively too much weight to top development. An average rating for each plot was obtained by using four criteria of results—total stand of 1–0 and percentage of good 2–0 as measures of yield, and weight and balance as measures of development. For the lightly fertilized plots this scheme of rating gave results very similar to those obtained from the earlier rating, whereas for the heavily fertilized plots the results were less similar, emphasizing the need for consideration of the quantities applied to the soil. This system of ranking the fertilizers according to the better of the two quantities produced the results shown in Figure 10. This is believed to be the most reliable and usable portrayal of results that can be reported at this time. Of course the nurseryman may wish to obtain quotations of current prices and rearrange the data in terms of relative results obtainable from each dollar spent for material, freight, and labor. Such computation is beyond the scope of this circular, but the quantities applied per acre show a sufficient range to indicate the value of this next step toward practical application.

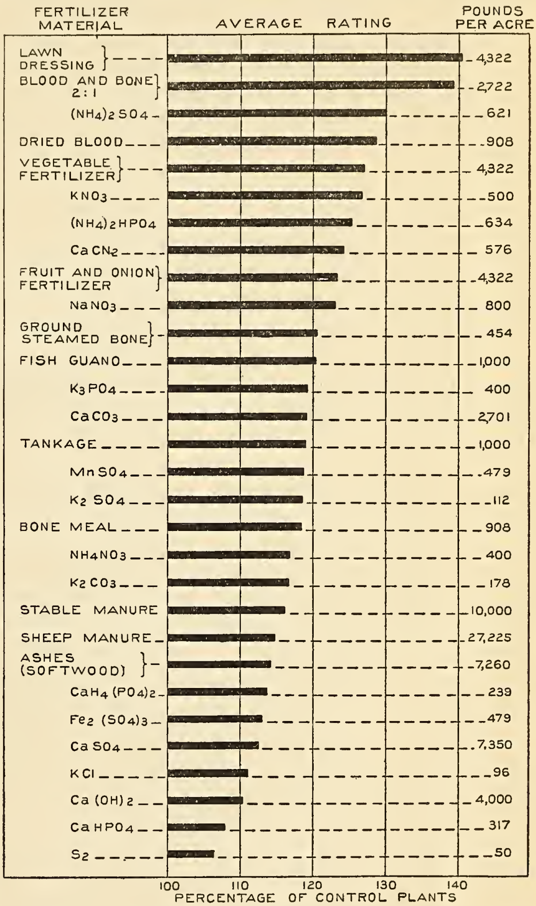

FIGURE 10.—Results of fertilization rated on the basis of yield and development of 2–0 western yellow pines

COMPARISON OF MATERIALS

Brief consideration of the materials rated in Figure 10 seems worth while.

The lawn dressing was a commercial mixture reported to be made up of superphosphate, bone meal, tankage, and guano, and containing 4.6 per cent nitrogen and 9.8 per cent phosphoric acid. Its humus value appears to be high. Its effect on western yellow pine seedlings is shown in Figure 11.

Dried blood and ground bone in the ratio of 2:1 have been used to advantage in several trials at the Savenac nursery. Bone meal usually contains about 20 per cent phosphoric acid and 4 per cent nitrogen, which slowly become available in the soil. They become available more rapidly when the meal is steamed and finely ground or pulverized. In discussing fertilizers, Voorhees (*34*) spoke of dried blood as

> one of the most important * * * because it is one of the most concentrated, one of the richest in nitrogen of the organic nitrogenous fertilizing materials. It is one of the best, since its physical content is such as to permit of its very rapid decay in the soil during the growing season.

Dried blood usually contains 10 to 14 per cent of nitrogen.

Soils rich in lime showed almost as good results from fertilization with ammonia salts as with nitrates, according to early experiments by Wagner (*35*), reported by Palladin and Livingston (*23*), but ammonia salts had but little value for soils poor in lime. Although lime was deficient in the soil at the Savenac Nursery, ammonium sulphate gave better results than sodium nitrate. The former usually contains 19 or 20 per cent of nitrogen as contrasted with 15 or 16 per cent in the latter. Possibly the nitrogen in the form of ammonia changes readily to the nitrate form in the soil, or else it may be that western yellow pine can utilize ammonia nitrogen as well as nitrate nitrogen. That this apparently rare ability is possessed by pea crops was indicated by Hutchinson and Miller (*18*). Ames and Simon (*2*) in Ohio found that both ammonium sulphate and sodium nitrate appreciably increased the solubility of potassium in various soils. Hall (*11*) in reporting the results of Rothamsted experiments, suggested that a mixture of these two materials may be advisable, because one, the sodium nitrate, acts early and the other acts later, and because their influence on soil reaction is opposite. In the experiments at the Savenac Nursery the reaction of the dry fertilizer materials was tested, as was also that of soil in the field plots, before and two years after the application. Although the significance of reaction tests with the isolated dry fertilizers is doubtful, it is interesting to note that sodium nitrate as a fertilizer rated a pH value of 5.7, whereas ammonium sulphate had a value below 4.9. The pH value of the soil before fertilization was 6.4. After two years this was changed by sodium nitrate to 6.5 and by ammonium sulphate to 6.1. Although western yellow pine is probably not sensitive to such small changes in soil reaction, the tendencies may be important when repeated applications are made. The results obtained at Rothamsted are particularly worthy of consideration because of the long period of years during which the experiments have been in progress there.

Hall further recommended that a choice between nitrate of soda and sulphate of ammonia be determined by external conditions such as the crop to be grown, the amount of calcium carbonate in the soil, the supply of dormant or available potash, and the effect of the materials on the tilth of the soil. He found that unless there was sufficient calcium carbonate in the soil the constant use of sulphate of

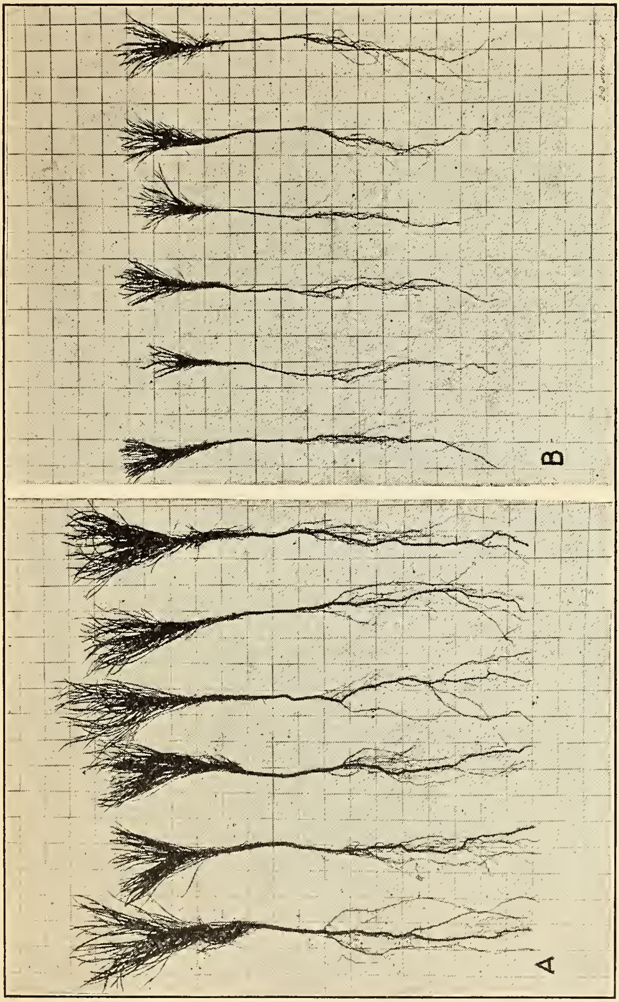

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FIGURE 11.—EFFECT OF FERTILIZED SOIL ON 2-0 WESTERN YELLOW PINE

A, Seedlings fertilized with a commercial mixture of superphosphate, bone meal, tankage, and guano, containing about 5 per cent nitrogen and 10 per cent phosphoric acid; B, unfertilized seedlings

ammonium salt by molds and microörganisms, while crop failures
The acidity was ascribed to the extraction of nitrogen from the ammonium salt by molds and microorganisms, while crop failures were attributed to acidity indirectly through the suspension of nitrification by bacteria. The Rothamsted researches further indicate that the repeated use of nitrate of soda causes soil to become wet and, if disturbed before it is dry, to poach badly, losing its friability.

That this may be due to hygroscopicity seems to have been discredited by moisture determinations. Hall explained the phenomenon by saying that the plants take up more of the nitric acid than of the soda, leaving soda to combine with carbonic acid from the roots. Even small quantities of the resultant sodium carbonate are sufficient to deflocculate clay, injuring its texture, and causing the loss of fine particles by leaching.

To sum up these observations in relation to the problem at the Savenac Nursery, it may be said that while the lack of limerock particles in the soil may be an obstacle to the use of ammonium sulphate, the bad cumulative effect of sodium nitrate on the physical condition of the soil may be more serious, because it seems less likely that applications of lime can successfully restore good tilth when the nitrate of soda itself has a basic reaction in the soil. Furthermore, in the first trials sulphate of ammonia gave the better promise of good crop response.

The vegetable fertilizer was a commercial mixture which ranked fifth in the list of substances tested. Like the lawn dressing this was composed of superphosphate, fish, tankage, and sheep guano. It appeared to have considerable humus value, but was classed a little lower than the lawn dressing in content of available plant food. It was reported to contain 2 per cent nitrogen, about 5 per cent available phosphoric acid, and 2 per cent soluble sulphate of potash.

The next three substances listed in Figure 10—potassium nitrate, ammonium acid phosphate, and calcium cyanide—probably owe their high rating primarily to their nitrogen content. Calcium cyanide usually contains about 20 per cent nitrogen. In using cyanide it should be remembered that it is poisonous to animal life. Allison et al. (*1*) in making field experiments with synthetic nitrogenous fertilizers found cyanide usually not so satisfactory as other sources of nitrogen, chiefly because so many factors influenced the rate and manner in which the material is decomposed in fertilizer mixtures or in the soil. If it be used, they recommend that it be applied early in the spring or at least 10 days before seeding. If applied at the time of seeding, it may retard early growth and delay maturity. Keitt (*19*) stated that cyanides are inferior to sulphate of ammonia except on acid soils.

Next in order is the so-called fruit and onion fertilizer, another commercial mixture of superphosphate, guano, and tankage. It was supposed to contain about 3 per cent nitrogen, 5 per cent phosphoric acid, and nearly 10 per cent of soluble sulphate of potash.

Some of the properties of sodium nitrate and bone meal have already been mentioned. Analysis of the fish guano or herring meal that was used indicated that it contained 11.8 per cent nitrogen, 4.8 per cent phosphoric acid, and 1.1 per cent potash. These figures, however, represent total amounts of which only part is immediately available for use by plants. Potassium phosphate, calcium carbonate, manganese sulphate, potassium sulphate, and tankage all were ranked much alike in an intermediate position in Figure 10. Tankage is a very variable product. The sample used was supposed to contain 7½ per cent of ammonia and 28 per cent bone phosphate.

For correcting extremes of soil reaction lime has already been used in practice at the Savenac Nursery. Other functions of lime in the

soil should not be overlooked. According to Shorey (*28*), lime improves soil structure, stimulates the decomposition of organic matter, and sometimes may serve directly as plant food or to increase the availability of such minerals as potash. Therefore it would seem that, where soils are showing the effects of intensive cropping, lime may be found beneficial; but it should not be applied repeatedly without complementary fertilization, if productivity is to be maintained. Halverson (*12*) reported various plants that flourish on alkaline soil and others that appear to prefer acid soil. If Baker (*3*) was correct in his conclusion, that unless acidity or alkalinity reaches extreme points it does not limit the survival or growth of western yellow pine, and that physical character of the soil is a greater factor, the stimulating action of lime in forest nurseries may be found more useful than its neutralizing action.

In spite of their high humus and nutrient values, animal manures did not rate high in the last tests at the Savenac Nursery. This was a surprise, for previous trials such as those with Engelmann spruce were very successful. The results with spruce were much the same as those obtained from the use of blood and bone. The reasons for less favorable results from manures in the latest trials are not clear, but it is possible that the manure samples tested were not truly representative, because they were small and were drawn from rather heterogeneous material. The difficulty could not be ascribed to any natural variability of the local soil, because of the uniformity of growth in the numerous unfertilized check plots. Agricultural experience, moreover, supplies abundant evidence of the benefit to soil from the use of animal manures. In some preliminary studies recently made in Michigan, Herbert (*16*) reported best results from fresh poultry manure and next best from horse manure in fertilizing Norway spruce seedlings. There can be no doubt of the high value of such materials in any permanent system of soil management.

The use of superphosphate (acid phosphate) alone did not promise worth-while results, but when used together with nitrogenous fertilizer it appeared to benefit seedling development. One form of superphosphate gave better results than the simpler compound containing less phosphorus. (Fig. 10.) Superphosphate as used in the triangle experiment should not be confused with the cheaper and less effective ground rock phosphate which is sold as a fertilizer. It constitutes the raw material from which superphosphate is made by treatment with sulphuric acid.

Although Chancerel (*4*) found that calcium sulphate or gypsum, unlike other substances, stimulated the production of new roots on oak seedlings in his experiments, at the Savenac Nursery it produced no very marked response in the growth of western yellow pine and no appreciable response in pea vines. Erdman and Bollen (*7*) state that it can not be substituted for lime because it possesses no alkalinity. They refute the common idea that it hastens the decomposition of organic matter in soil, but they reaffirm its power to make native potassium in certain soils available to plants. However, nitrogen is more important than potassium in the nursery problem at Savenac, and Cubbon (*6*) observes that nitrate accumulation is retarded on various soils by the addition of calcium sulphate.

INTERACTION OF CHEMICAL FERTILIZERS

In this preliminary report some mention has necessarily been made of the commonly recognized interaction between materials. Other instances should be mentioned also. For instance, lime should never be mixed with ammonium sulphate, since nitrogen is then lost to the atmosphere in the form of free ammonia gas. Similarly, Fraps (*10*) recommends that not more than 4 per cent of calcium carbonate be mixed with superphosphate because it attacks water-soluble phosphoric acid, changing it largely into an insoluble form not available for the use of plants. Such action, he says, is more complete in the presence of nitrate of soda than in the presence of sulphate of potash. Allison et al. (*1*) found that when cyanamid was mixed with superphosphate in large proportions the poor results were probably due to the transformation of a portion of the cyanamid to dicyanodiamide, a compound which they say is not only unavailable, but toxic for some crops and for nitrifying bacteria. But practical warnings against such difficulties are given by Fletcher (*9*). Chemical reactions, after fertilizing the soil, often produce what have been termed "secondary effects," which seem to influence crops as much as the direct action of fertilizers. For example, the unexplained opposite effect of fertilizers on yield and development of pine seedlings as noted below probably should be attributed to secondary effects in the soil. Apparently the same forces which reduce germination in some way, such as by making the soil a better medium for certain fungi, also increase the development of the survivals. It is likely that different species would be affected quite differently in this respect. Truog et al. (*32*) state the probability that at least three factors inherent in the seed or sprout itself determine the effect of fertilizers on the germination of seed, viz, osmotic concentration of the sap of the seed, osmotic concentration of the sap of the sprout, and quantity of protective covering on the sprout.

SUMMARY

Early experiments at the Savenac Nursery, Haugan, Mont., resulted in increased development of pine planting stock grown on soil fertilized with nitrogenous materials. However, the seedlings showed some signs of increased susceptibility to disease in the nursery and they did not survive field planting as well as similar unfertilized seedlings.

More intensive experiments with Engelmann spruce proved that the naturally slow growth of this species in the nursery could be safely stimulated by fertilization, and that the better developed, more easily handled planting stock that was produced survived field planting better than similar unfertilized trees. By using moderate applications of dried blood and bone meal or heavy applications of sheep manure at least a year was saved on the 5-year or 6-year period formerly necessary for the production of suitable planting material. A few tests indicated that sodium nitrate in solution may be advantageously used as a top-dressing for 2–0 Engelmann spruce beds in order to eliminate the weaker and crowded individuals and force the growth of the better trees.

More complete fertilization was tried in recent experiments for the purpose of studying means of maintaining soil fertility. Out

of 21 trials of various mixtures of three common fertilizers as sources for nitrogen, phosphorus, and potassium, the best developed 2-year-old western yellow pines were found in a small group of plots fertilized with fairly large proportions of sodium nitrate mixed with moderate or small quantities of superphosphate or muriate of potash, or both. The five mixtures that in general may be taken as indicative of the mixtures to be recommended are given on an acre basis in Table 6.

TABLE 6.—*Fertilizer mixtures employed at Savenac Nursery most suggestive of fertilizers for outside use*

Plot No.	Sodium nitrate	Superphosphate	Muriate of potash	Plot No.	Sodium nitrate	Superphosphate	Muriate of potash
	Pounds	*Pounds*	*Pounds*		*Pounds*	*Pounds*	*Pounds*
77	320	240	0	79	320	80	60
74	480	160	0	78	320	160	30
76	480	0	60				

Standard fertilizing materials suitable for western yellow pine under conditions similar to those at the Savenac Nursery were compared in 60 simultaneous tests, including both heavy and light applications. Best results were obtained from a heavy treatment with a commercial mixture of superphosphate, bone meal, tankage, and guano containing 4.6 per cent nitrogen and 9.8 per cent phosphoric acid. A heavy treatment with dried blood and ground bone mixed in the ratio of 2:1 was the next most effective. Ammonium sulphate ranked third. Other common fertilizers varied much in the degree of their benefit to the seedlings, but there was a tendency for those high in nitrogen to yield best results. Although animal manures did not rate particularly high in trials where immediate crop responses were considered, their great value in permanent soil management is unquestioned. Maintenance of soil organic matter in adequate amounts is recognized as of prime importance. However, if bulky organic fertilizers can not be obtained locally in sufficient quantity, their use should be supplemented by the addition of more concentrated fertilizers.

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